FLORIDA STATE UNIVERSITY

Kévin Fossez
Assistant Professor
FRIB Bridge

FRIB Topical Program

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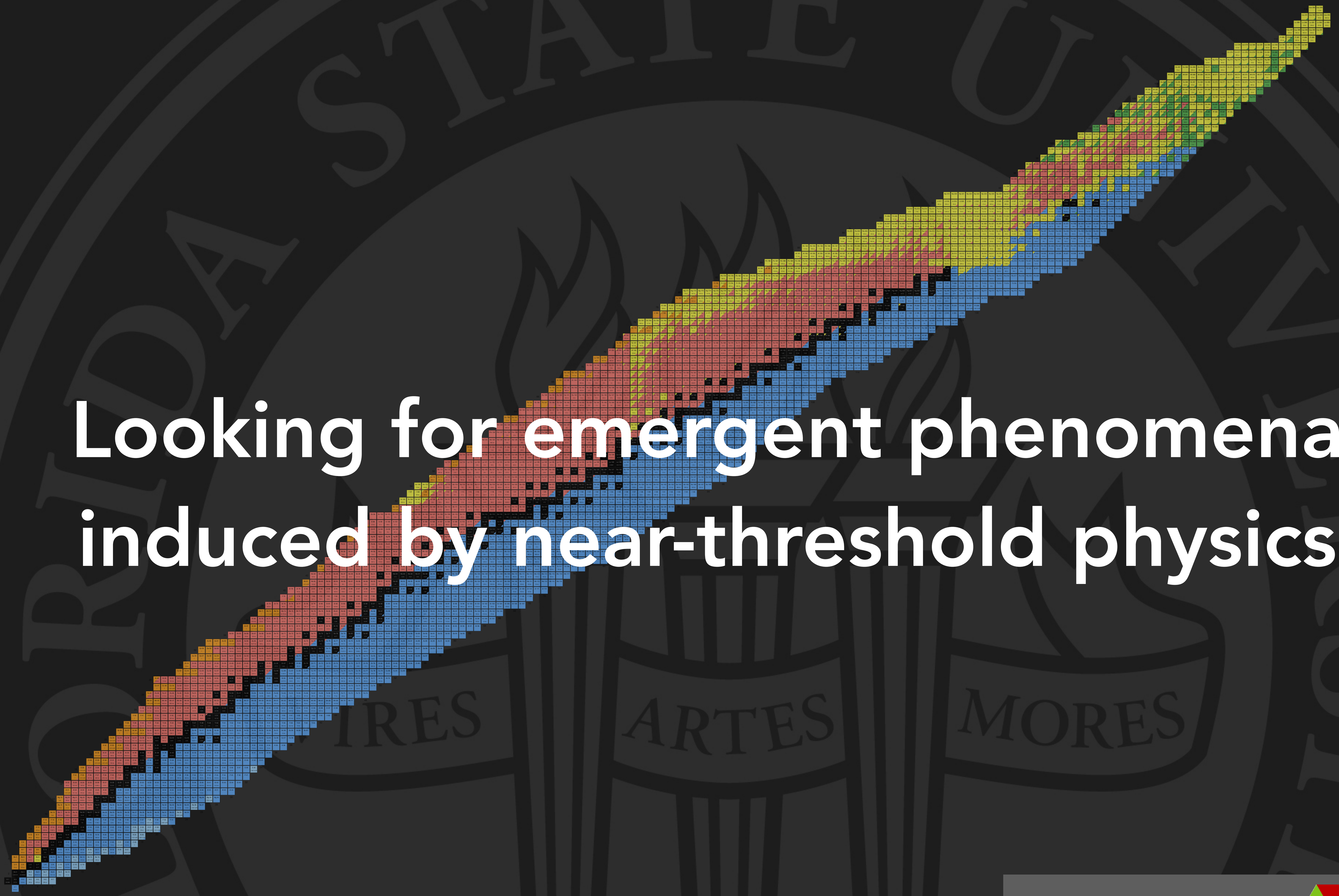
Looking for emergent phenomena induced by near-threshold physics



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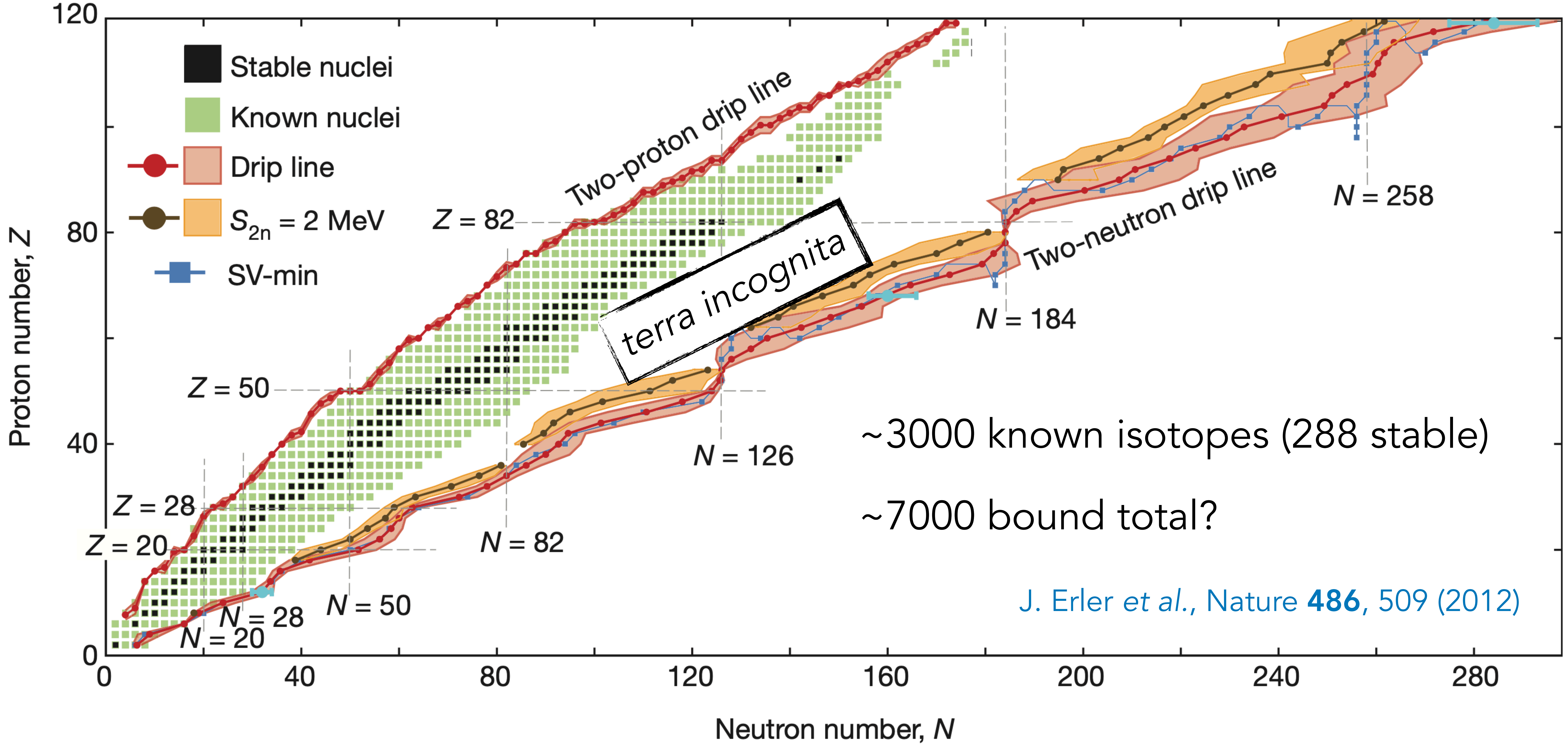
U.S. DEPARTMENT OF ENERGY | Office of Science

Argonne NATIONAL LABORATORY

DOE: DE-SC0013617 (Office of Nuclear Physics, FRIB Theory Alliance)

The exploration of the drip lines

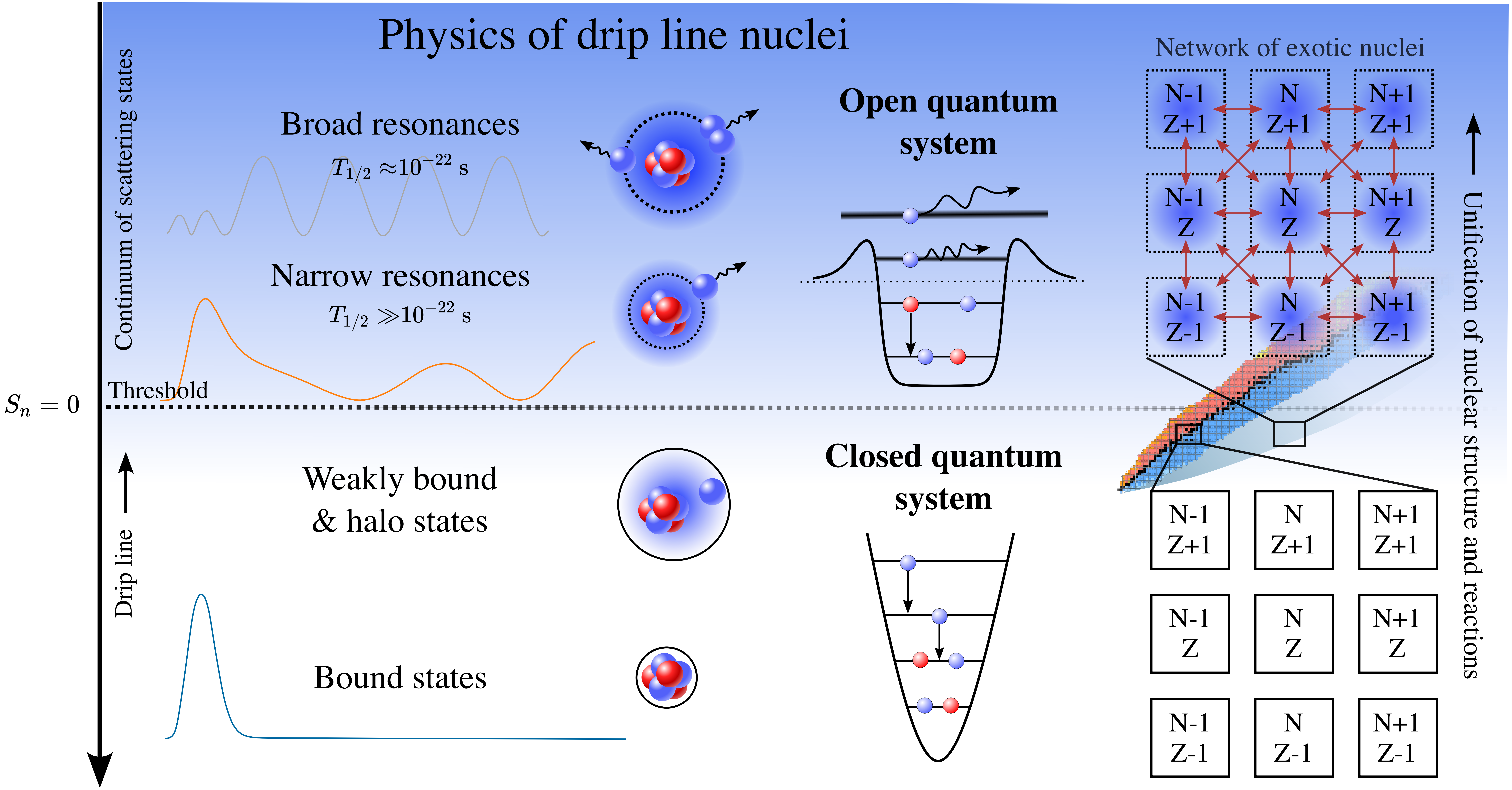
Established at N = 9 and Z = 13. Many new isotopes to discover on the neutron-rich side.



Some opportunities:

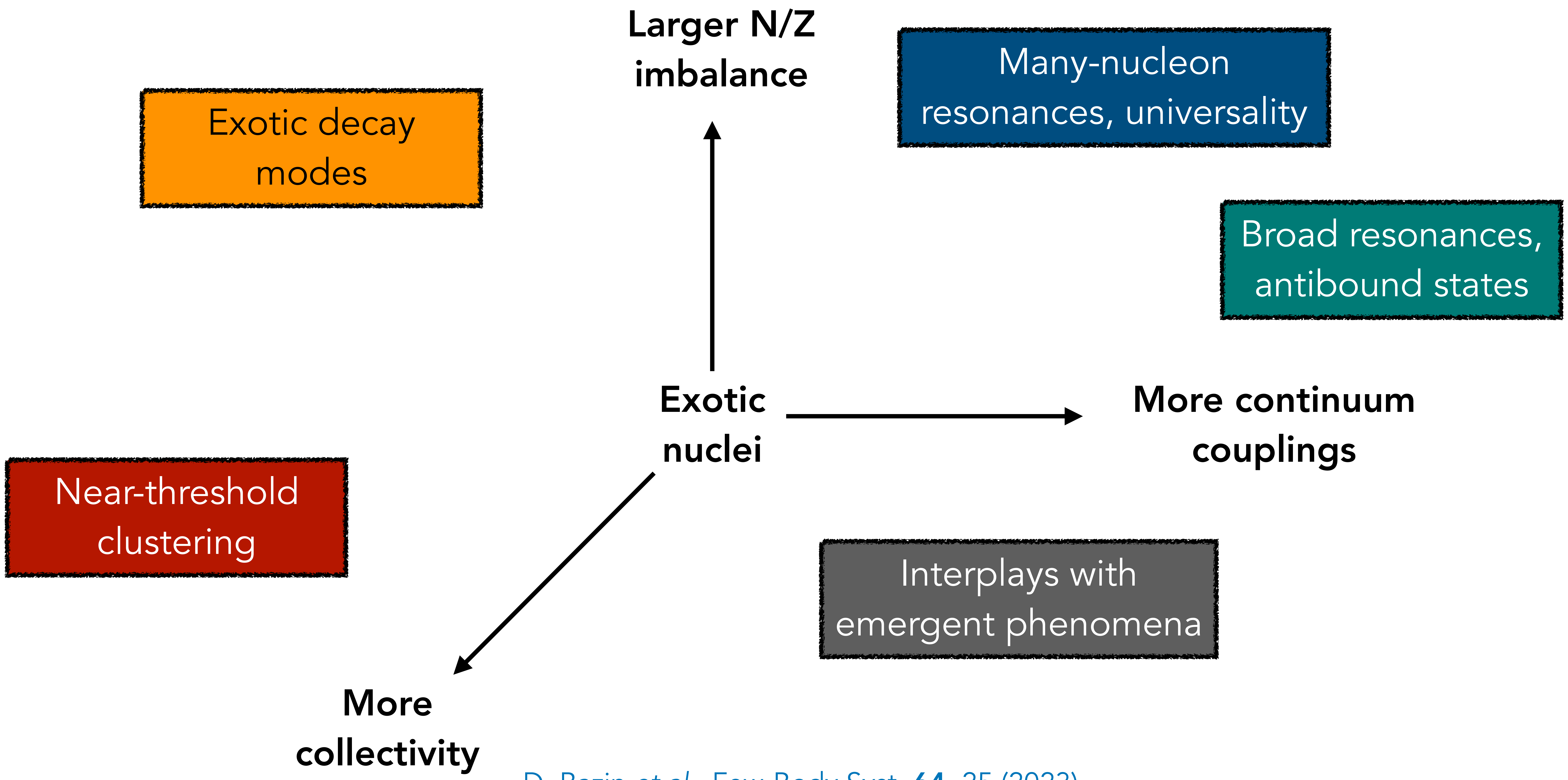
- Test of nuclear forces in extreme N/Z conditions.
- Strong constraints: an isotope exists or it does not.
- Finding new phenomena induced by near-threshold effects.

Where should we look first and why?


Physics of drip line nuclei
Continuum of scattering states
Broad resonances
$T_{1/2} \approx 10^{-22}$ s
Narrow resonances
$T_{1/2} \gg 10^{-22}$ s
Threshold
$S_n = 0$
Drip line
Weakly bound
& halo states
Bound states
Open quantum
system
Closed quantum
system
Network of exotic nuclei
N-1
Z+1
N
Z+1
N+1
Z+1
N-1
Z
N
Z
N+1
Z
N-1
Z-1
N
Z-1
N+1
Z-1
Unification of nuclear structure and reactions

Theoretical challenges in near-threshold physics

Drip lines, higher excitation energies.



D. Bazin *et al.*, Few-Body Syst. **64**, 25 (2023)

Theoretical approaches for near-threshold physics

Many methods developed over time, but in practice, only a few methods can go beyond 2 nucleons in the continuum.

Feshback projection formalism:

CSM, SMEC

Complex-scaling techniques:

Faddeev-Yakubowsky, lattice

↓

Limited to 5 particles (need further development to go beyond)

Berggren basis:

GSM, NCGSM, G-DMRG, CCT, IM-SRG, GCC, PRM

In theory, the GSM can have all nucleons in the continuum, but in practice it needs truncations beyond ~4-5 nucleons.

Resonating group method (reactions with structure):

NCSM+RGM, NCSMC, (NC)GSM-CC, Symplectic-NCSM

And more…

The (current) G-DMRG code can handle Hamiltonians of theoretical dimension up to dim $= 10^{11}$.

So far up to 9 particles in the continuum.

Gamow density matrix renormalization group

Configuration interaction + renormalization group.

S. R. White, Phys. Rev. Lett. **69**, 2863 (1992)

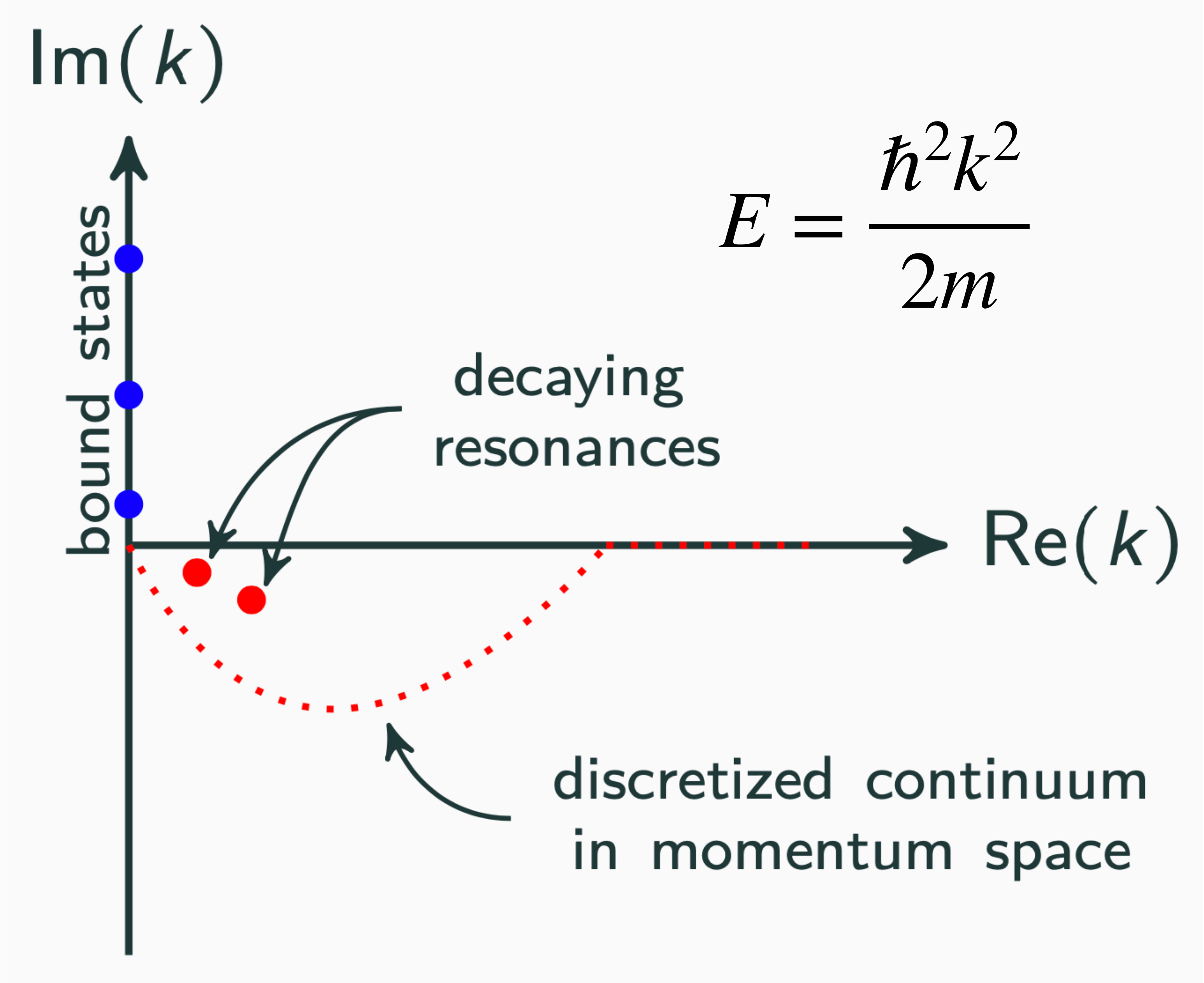
$$|\Psi^{A,J^\pi}\rangle_1 = \sum_{a,b} C^a_{b,i=1} \{ |\mathrm{SD}^{f_\mathscr{A}}_a\rangle^\mathscr{A}_0 \otimes |\mathrm{SD}^{f_\mathscr{B}}_b\rangle^\mathscr{B}_1 \}^{A,J^\pi}$$

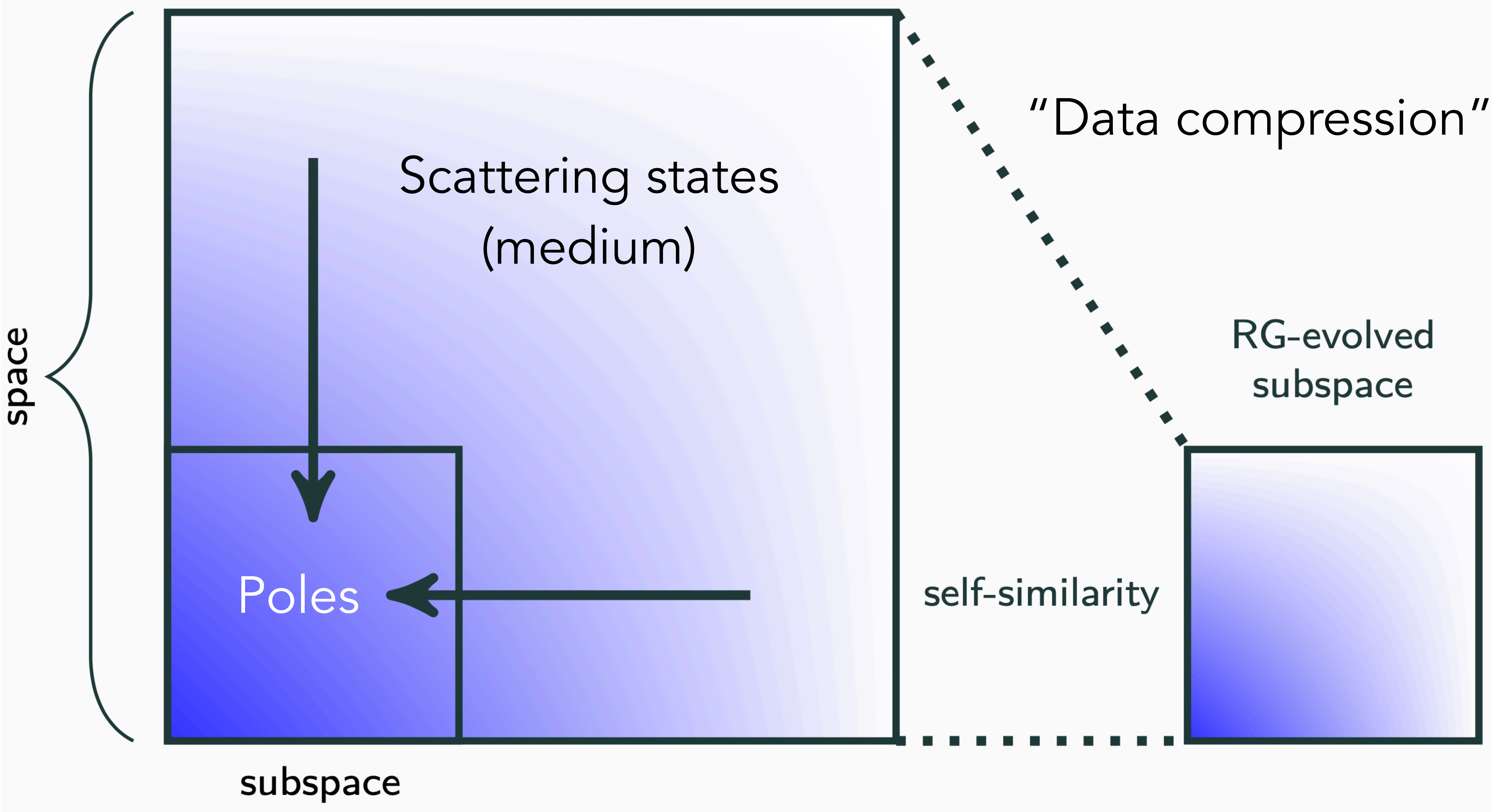
Reference space   Medium

$$\sum_{i=(b,r)} |k_i\rangle\langle\tilde{k}_i| + \int_{L^+} dk\, |k\rangle\langle\tilde{k}| = \hat{1}$$

T. Berggren, Nucl. Phys. A **109** 265 (1968)

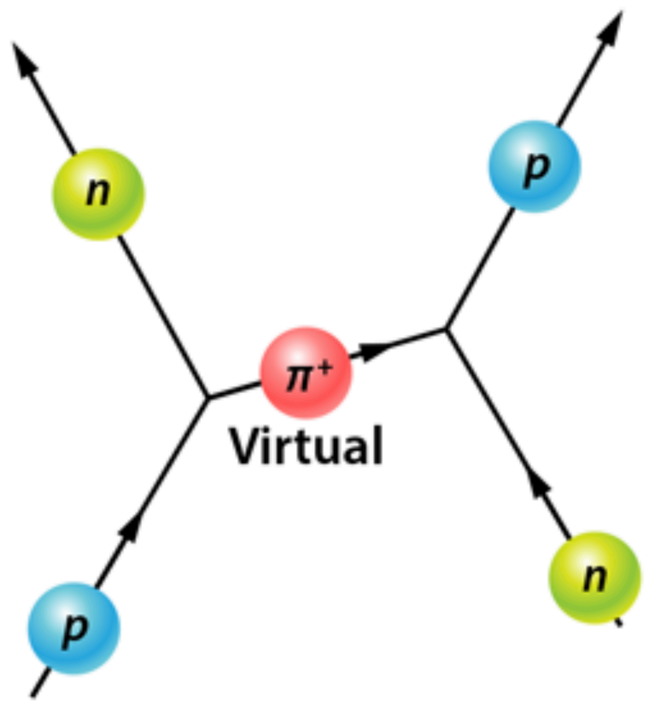
J. Rotureau *et al.*, Phys. Rev. Lett. **97**, 110603 (2006)

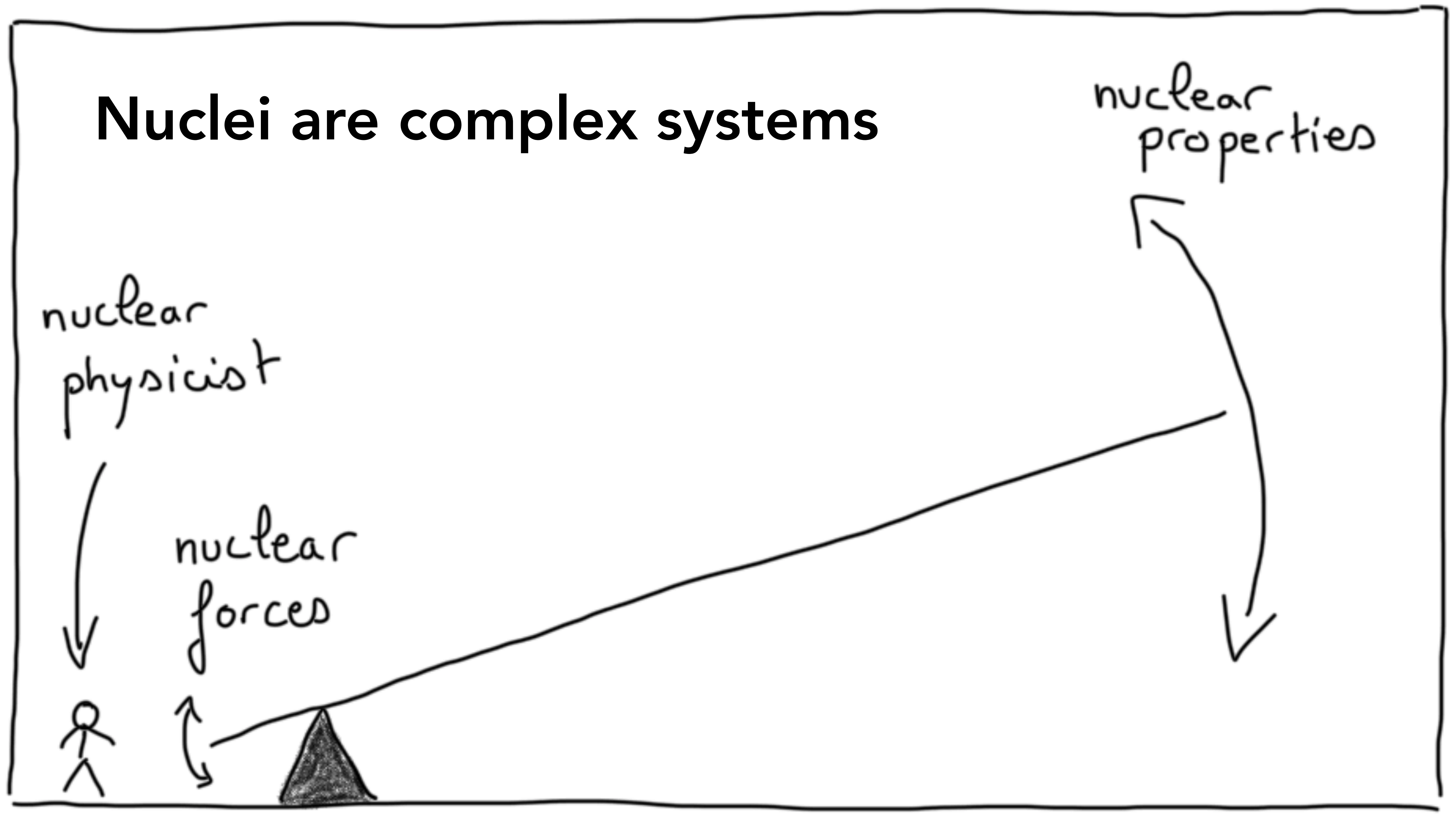


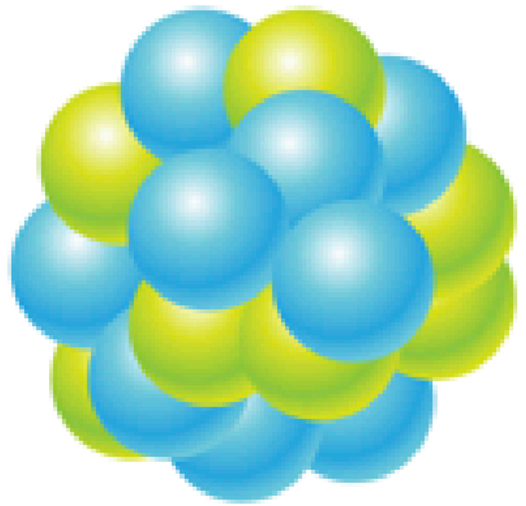


Studying drip line nuclei in practice

We want to have **predictive power** and to make **usable predictions (= precise enough).**







Small change in the input

↓

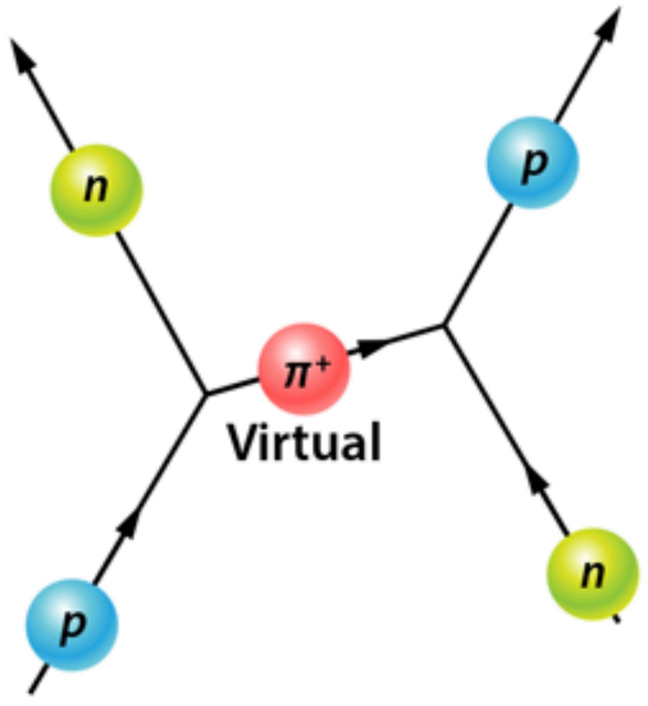
Large change in the output

Even if we had exact *ab initio* solutions including 1-, 2-, …, A-body continua, our representation of nuclear forces will always have some error that will be magnified in the many-body problem → **Emergent phenomena.**

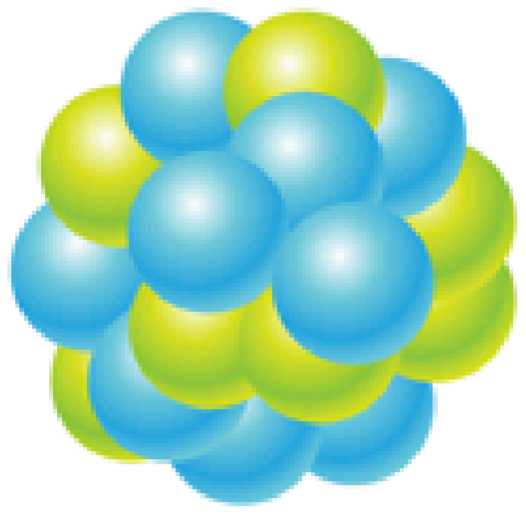
Current *ab initio* methods precise within ~ 1.0 MeV at best on binding energies → **We need EFTs.**

Nuclei are complex systems

Small change in the input → large change in the output.

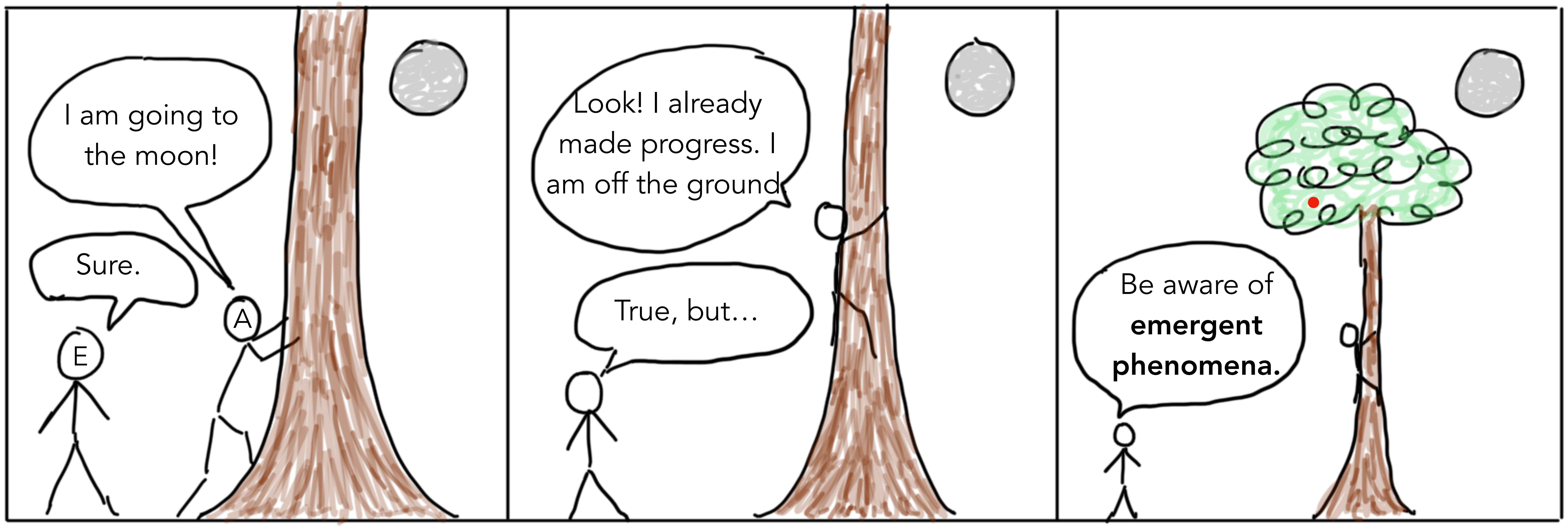


How do we go from nuclear forces to exotic nuclei?



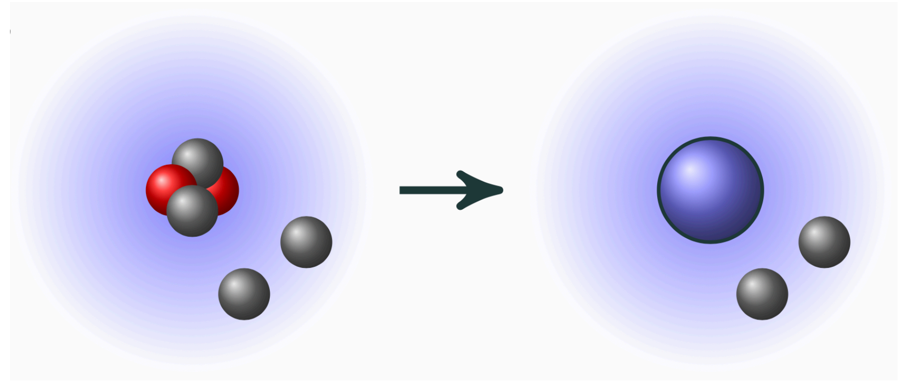
The ``moon"

Ms. EFT and Mr. Ab initio



We need EFTs for precision!

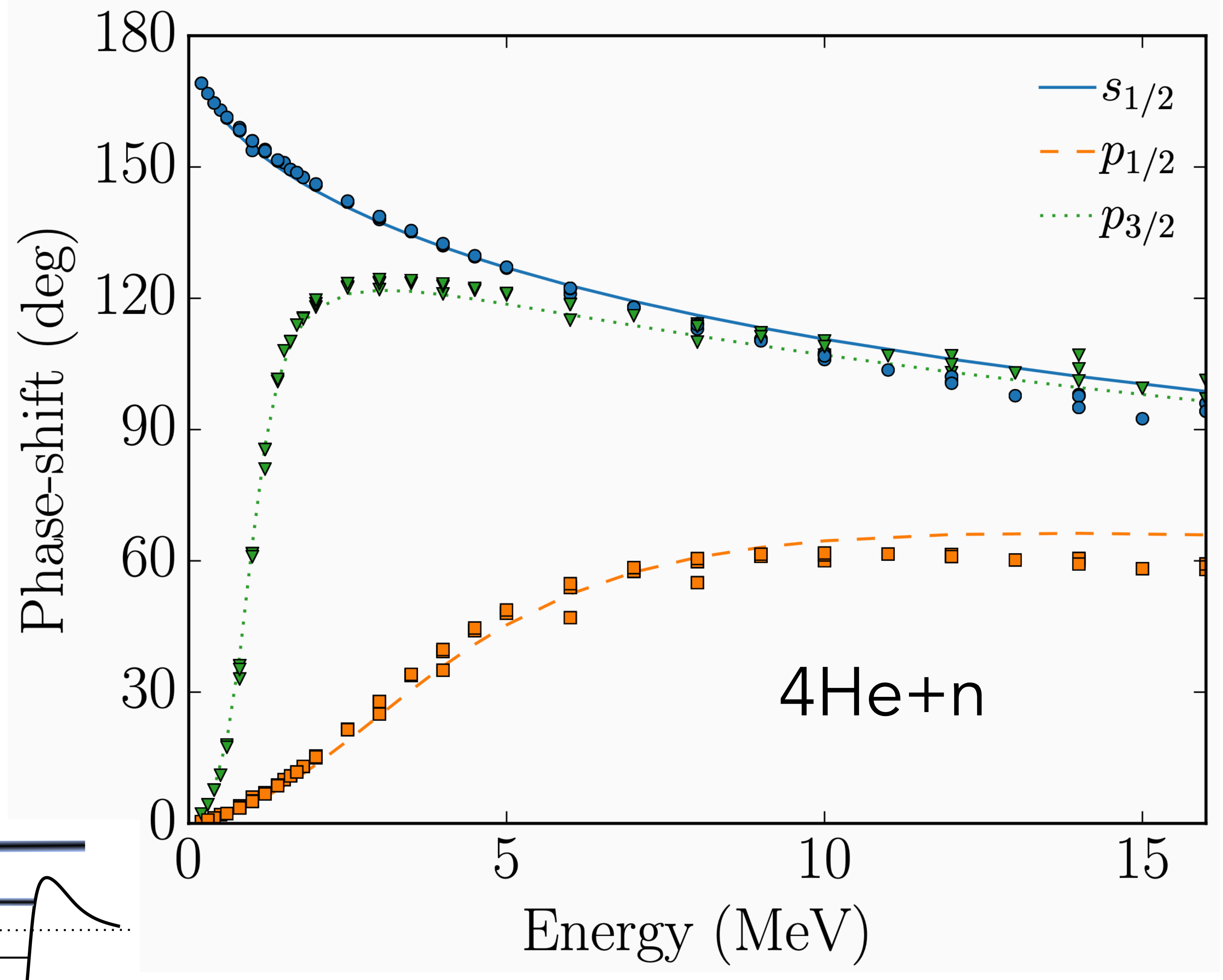
Studying drip line nuclei in practice

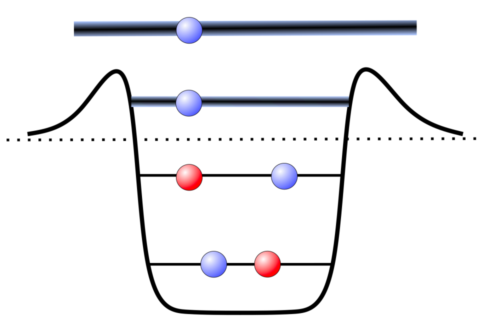


Building an EFT for the shell model appears to be the best compromise to deal with drip line nuclei.

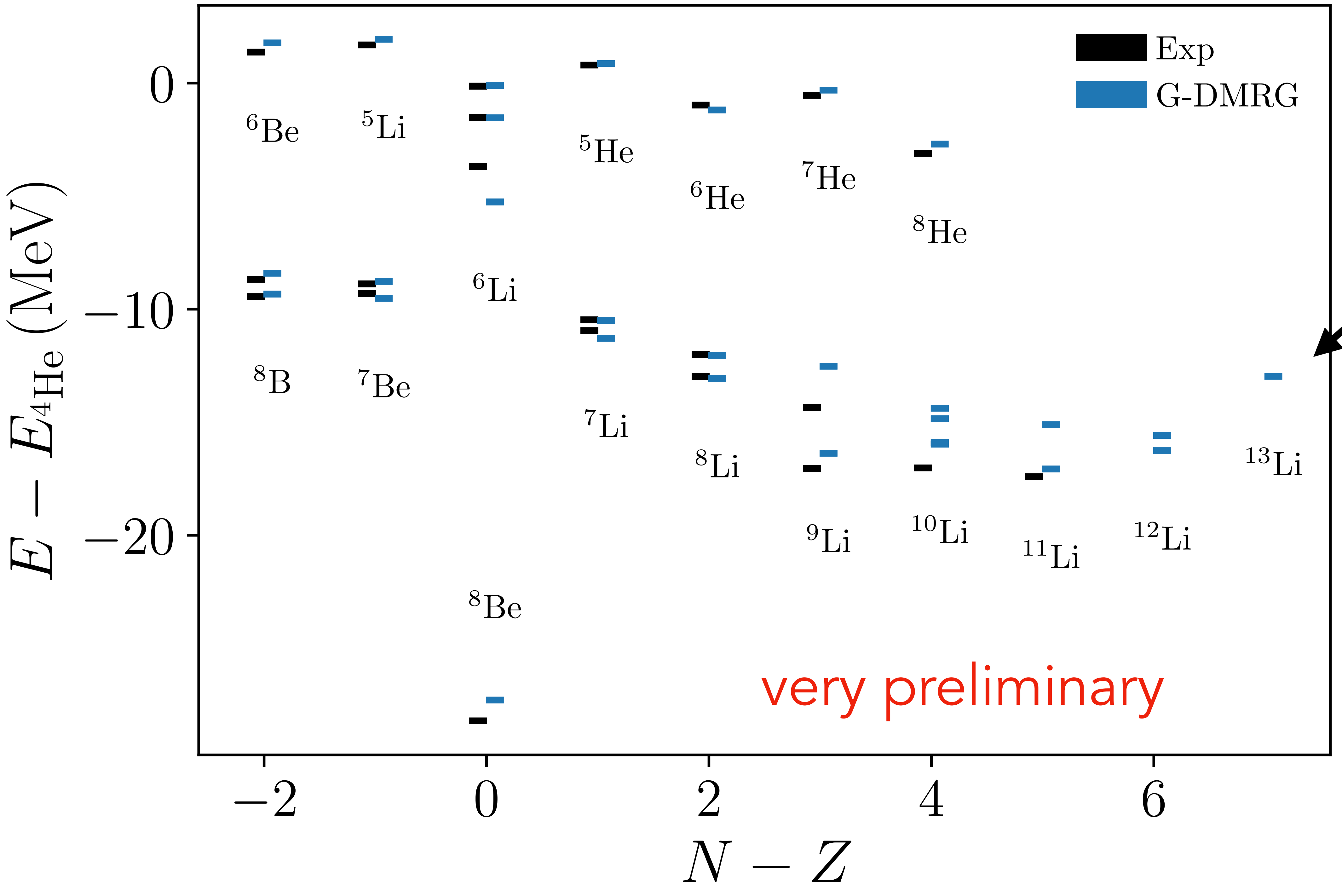
Still working on the details, but adjusting a phenomenological contact interaction in the EFT spirit promising.

Core-nucleon interaction must reproduce core-nucleon phase shifts.





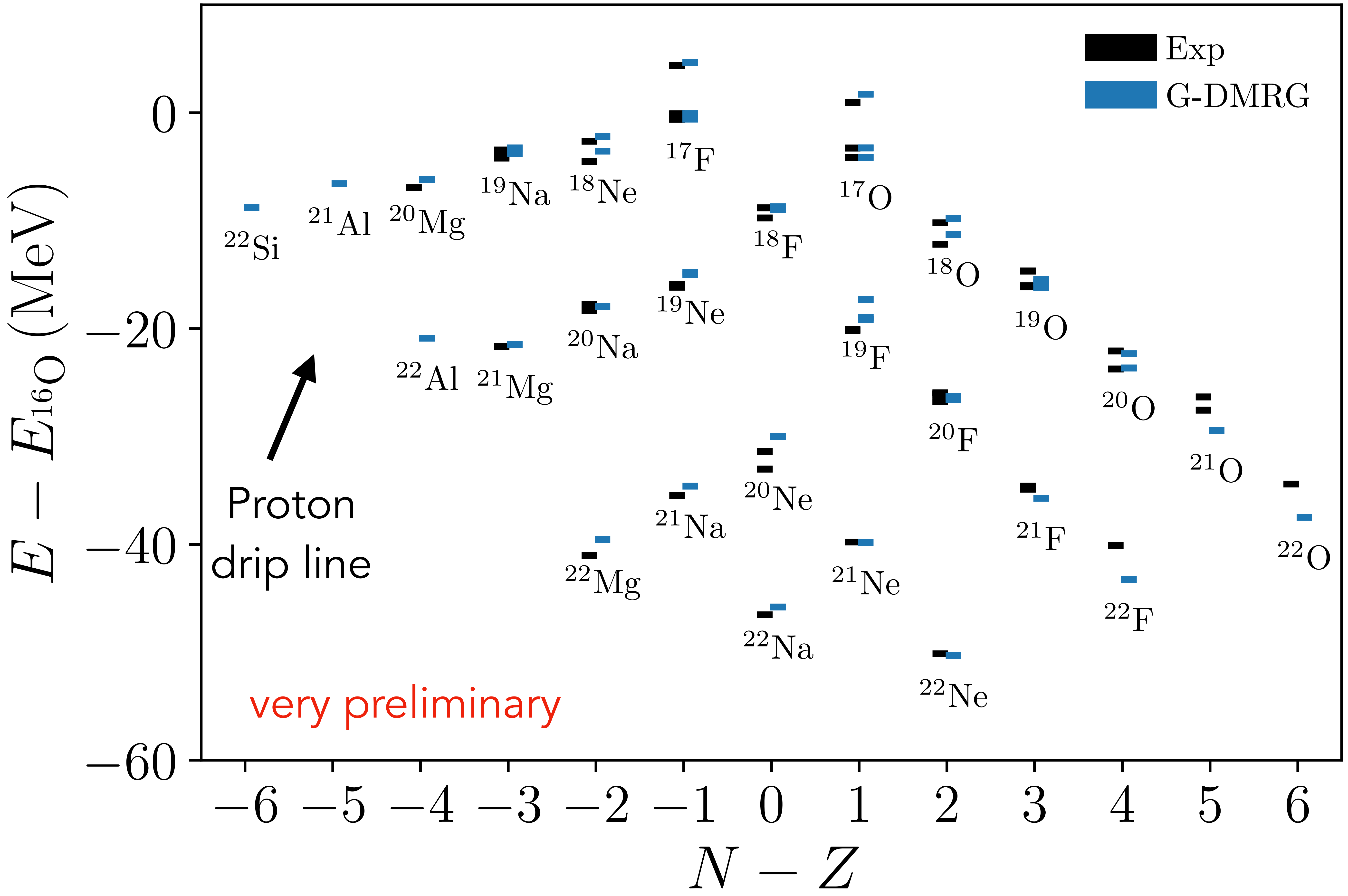
Then, nucleon-nucleon interaction adjusted on A+2,3 systems only.



Predictive and ``precise"

Studying drip line nuclei in practice

Similar results form an effective core of 16O in sd space with continuum (very preliminary):



Far from USDB but approaching current *ab initio* precision.

All nucleons can couple to the continuum (s1/2, d5/2, d3/2).

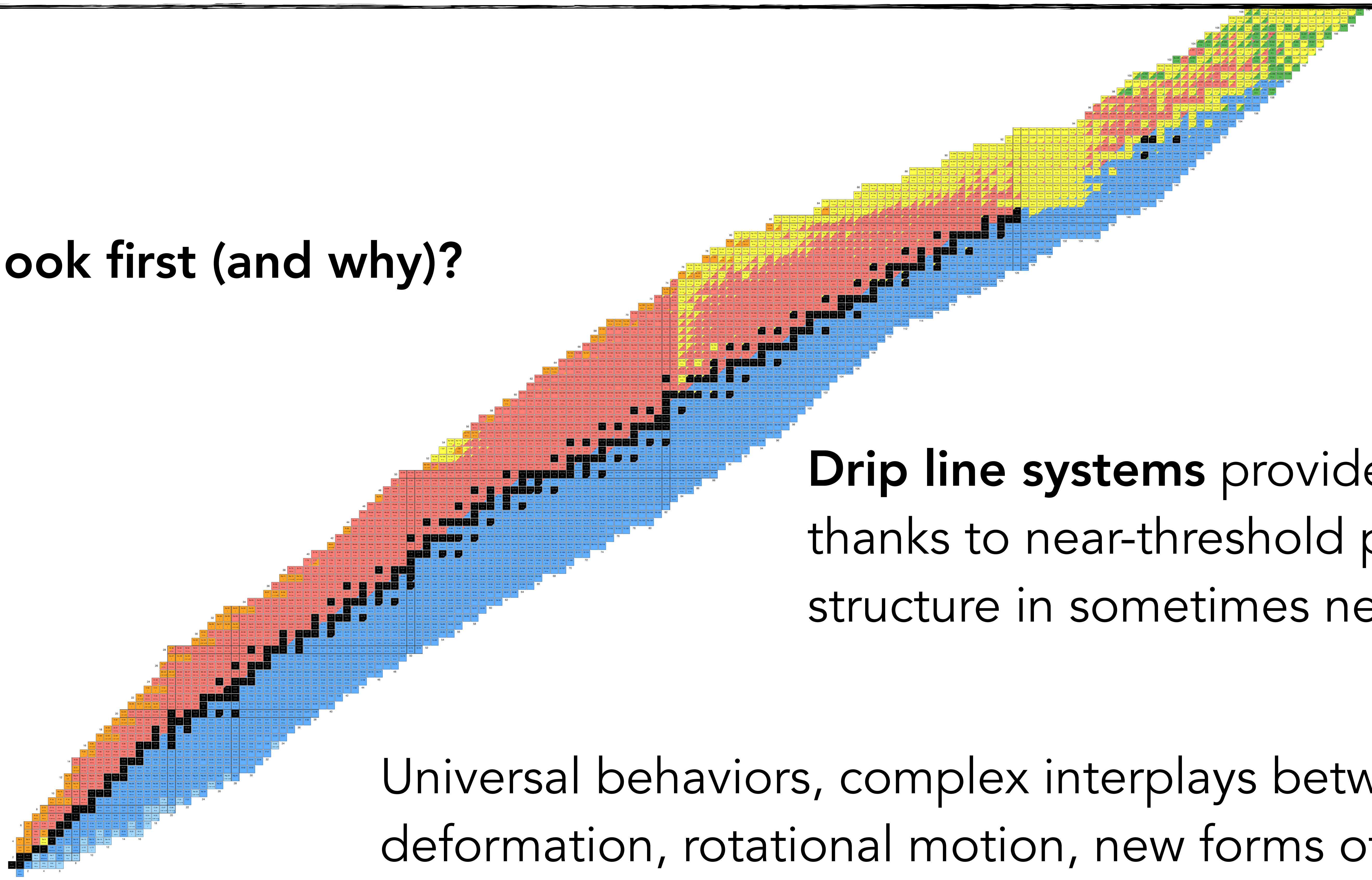
Extension to a core of 40Ca possible.

(The emergence of universality might make it possible to reach 60Ca.)

An (old?) idea for future high-impact FRIB experiments

Find the systems or areas of the nuclear chart where new/unique/sensitive emergent phenomena magnify less known aspects of nuclear forces.

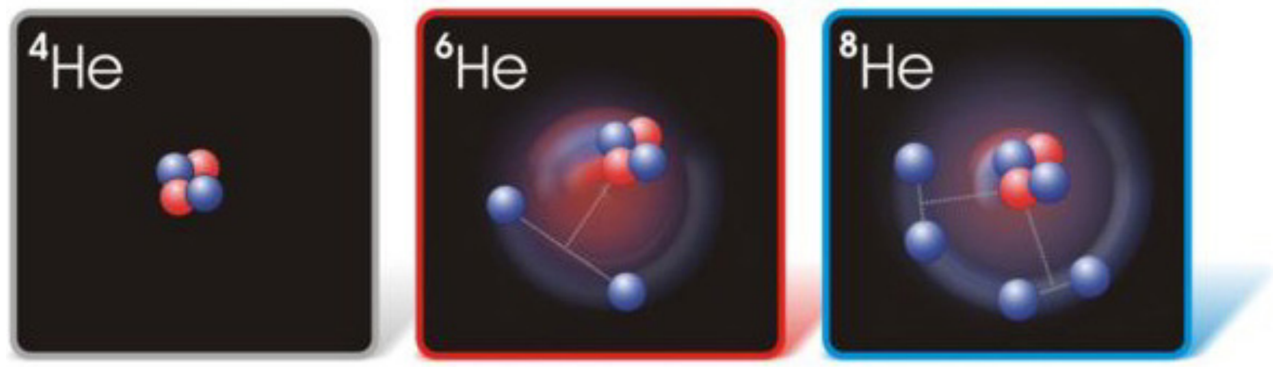
Where should we look first (and why)?



Drip line systems provide excellent opportunities thanks to near-threshold physics modifying nuclear structure in sometimes new and various ways.

Universal behaviors, complex interplays between decay and clustering, deformation, rotational motion, new forms of radioactivity…

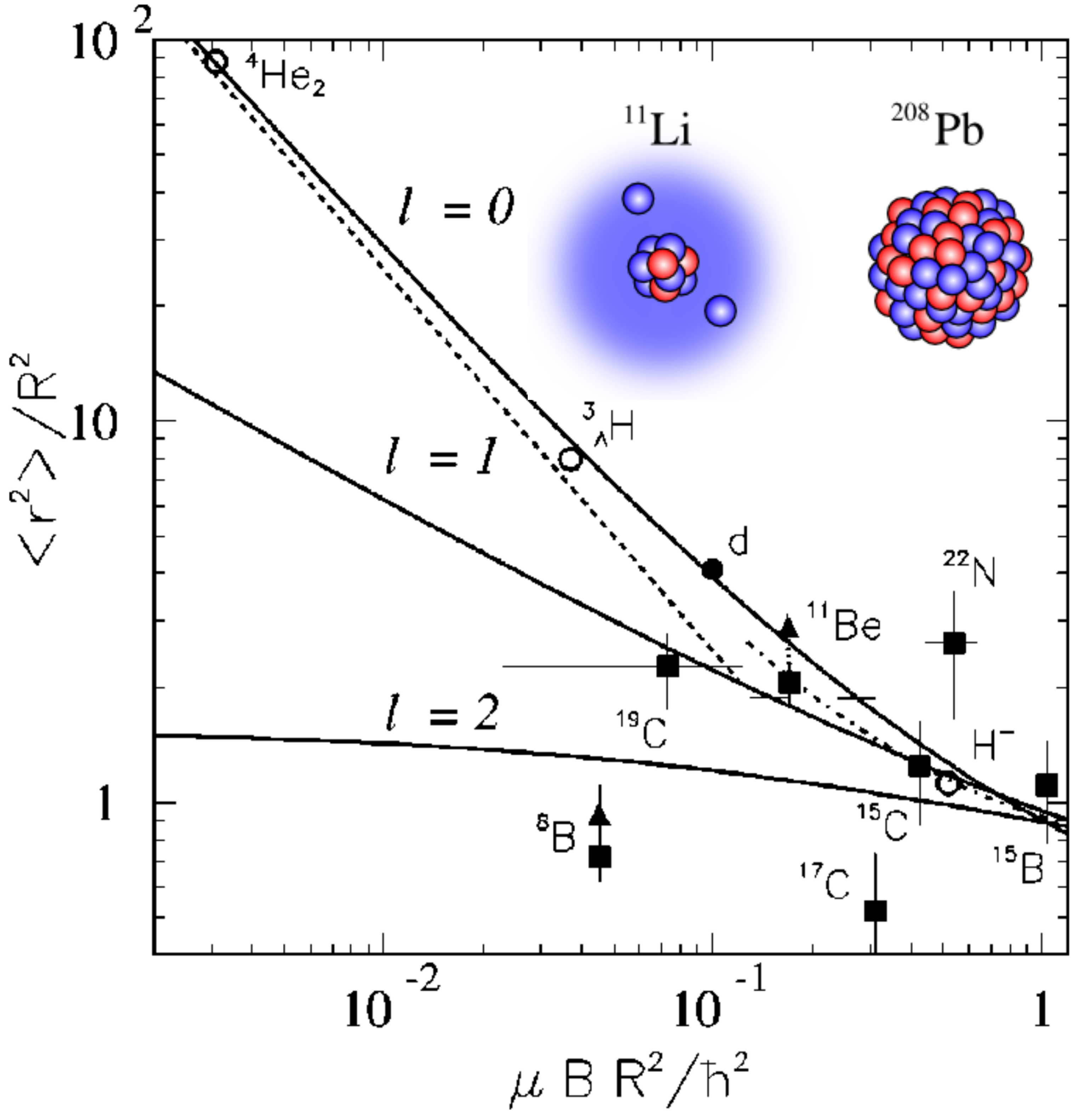
Known examples



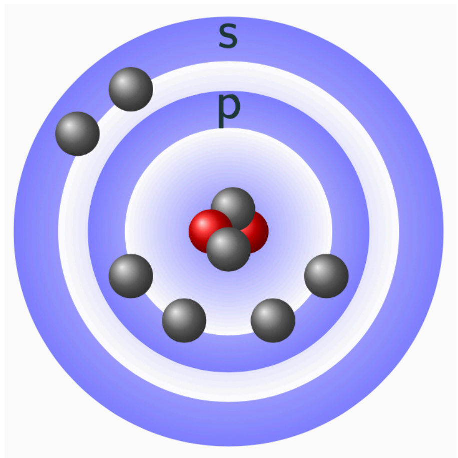
Halo structures

I. Tanihata *et al.*, Phys. Rev. Lett. **55**, 2676 (1985)

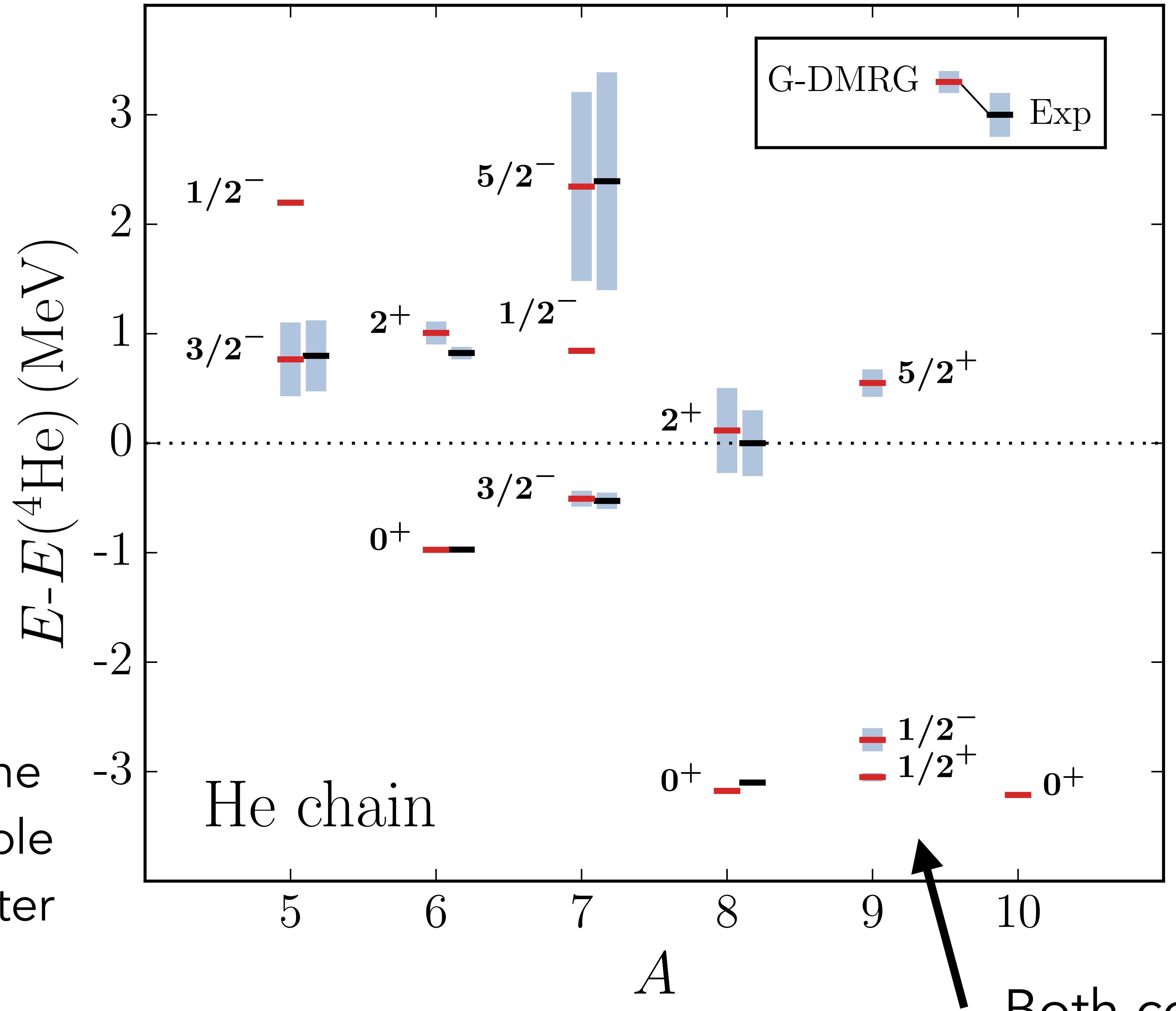
A. S. Jensen *et al.*, Rev. Mod. Phys. **76**, 215 (2004)

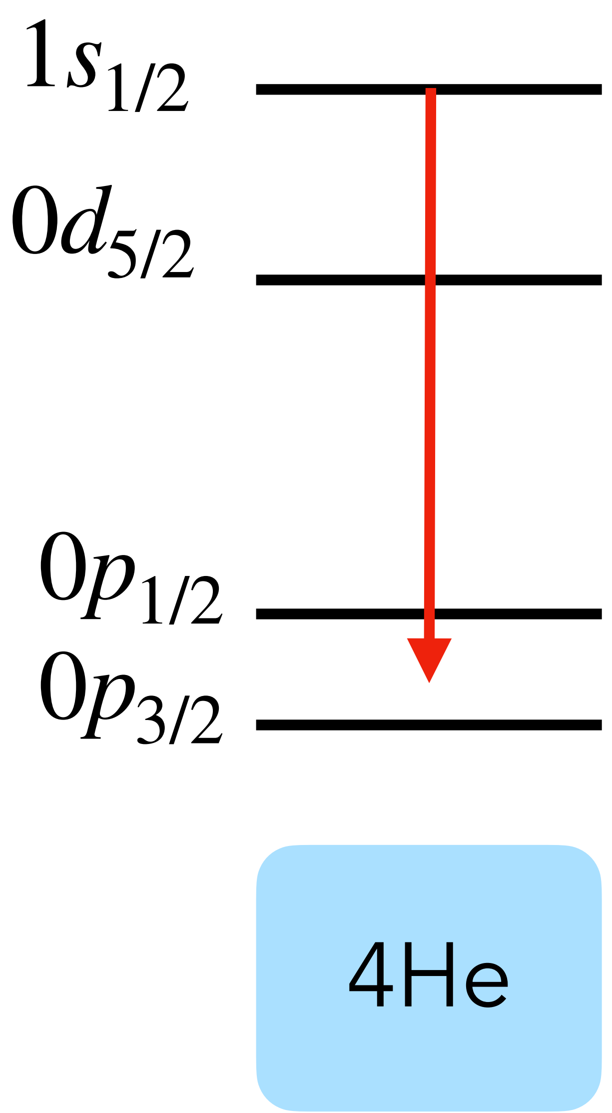


Many-body dynamic in the 6n-continuum: toward universal behaviors.



K. Fossez *et al.*, Phys. Rev. C **98**, 061302(R) (2018)





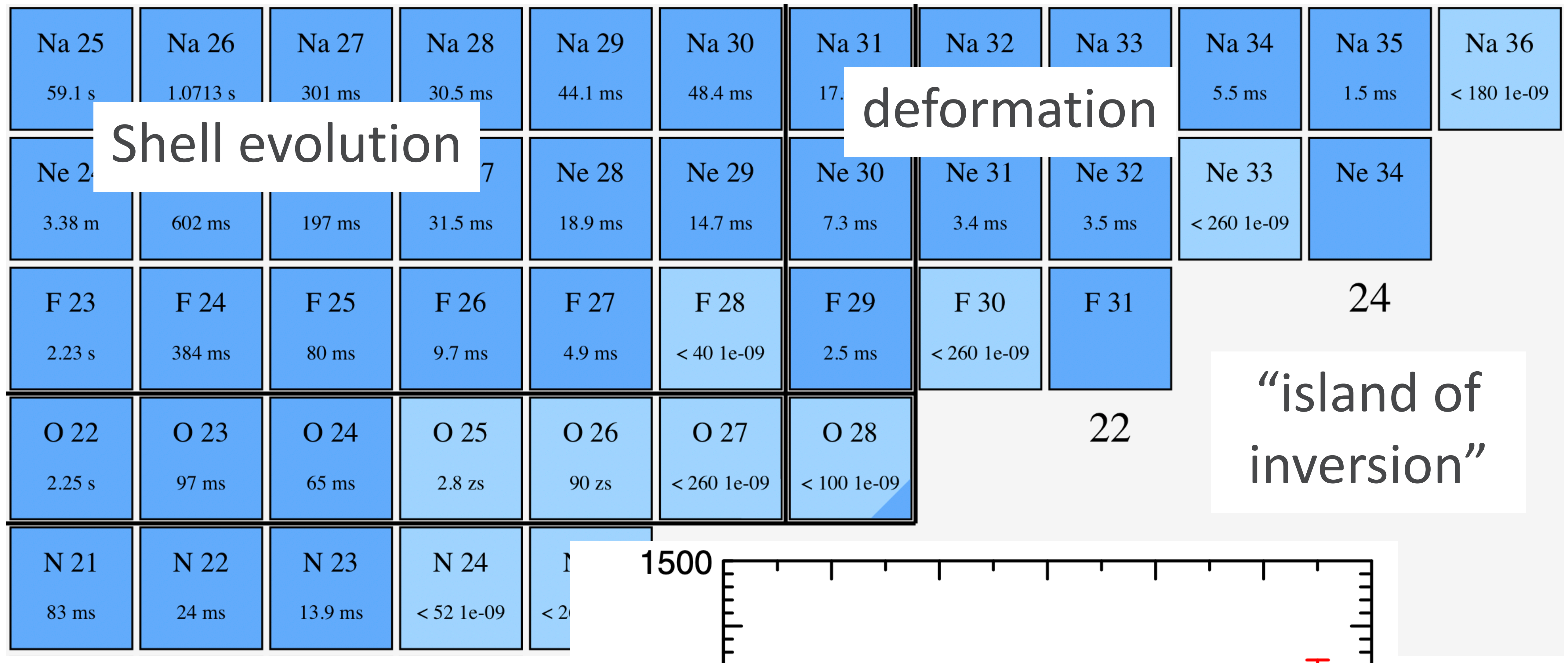
Only one adjustable parameter

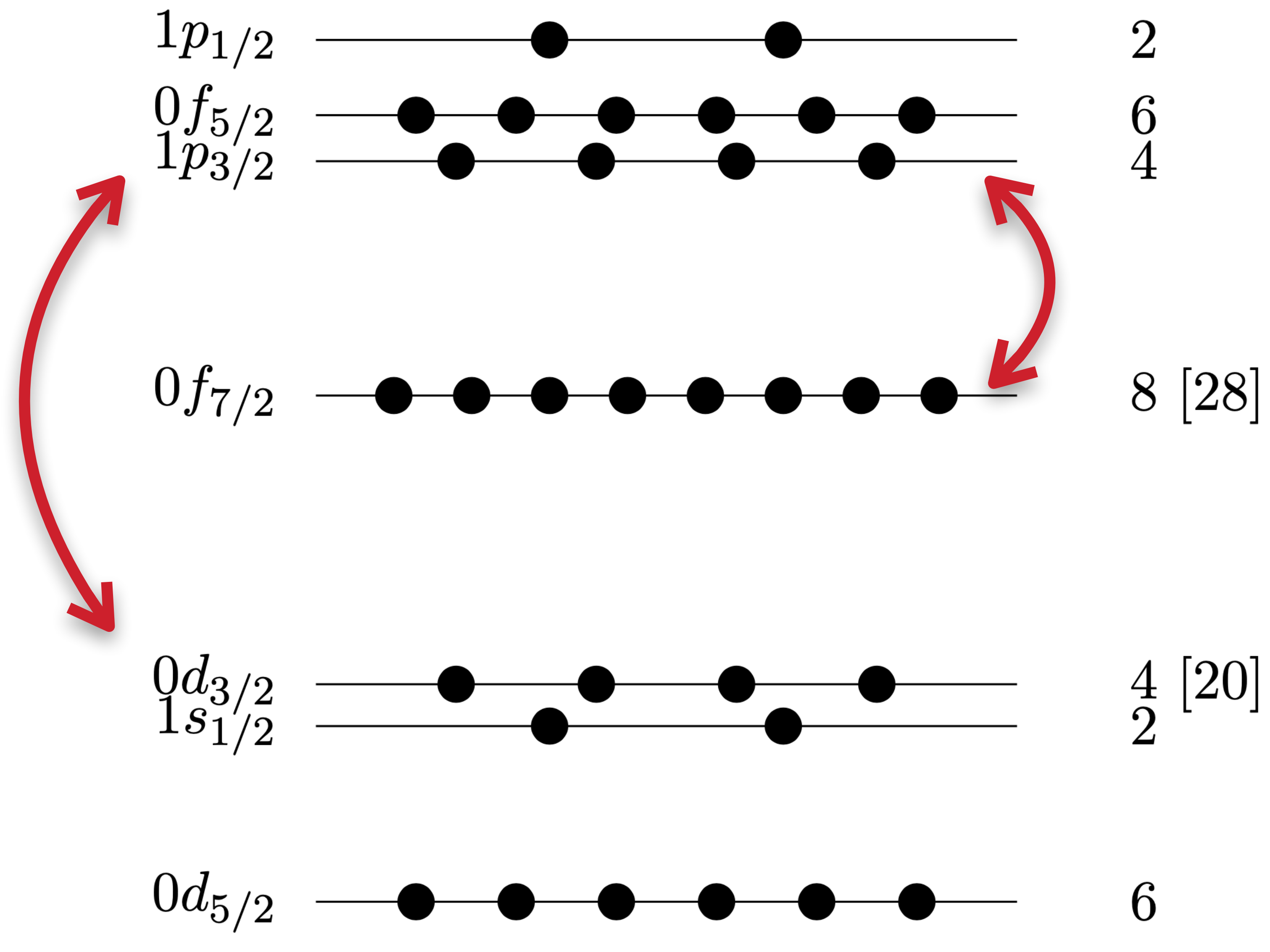
Both confirmed experimentally!

D. Votaw *et al.*, Phys. Rev. C **102**, 014325 (2020)

Continuum inducing deformation?

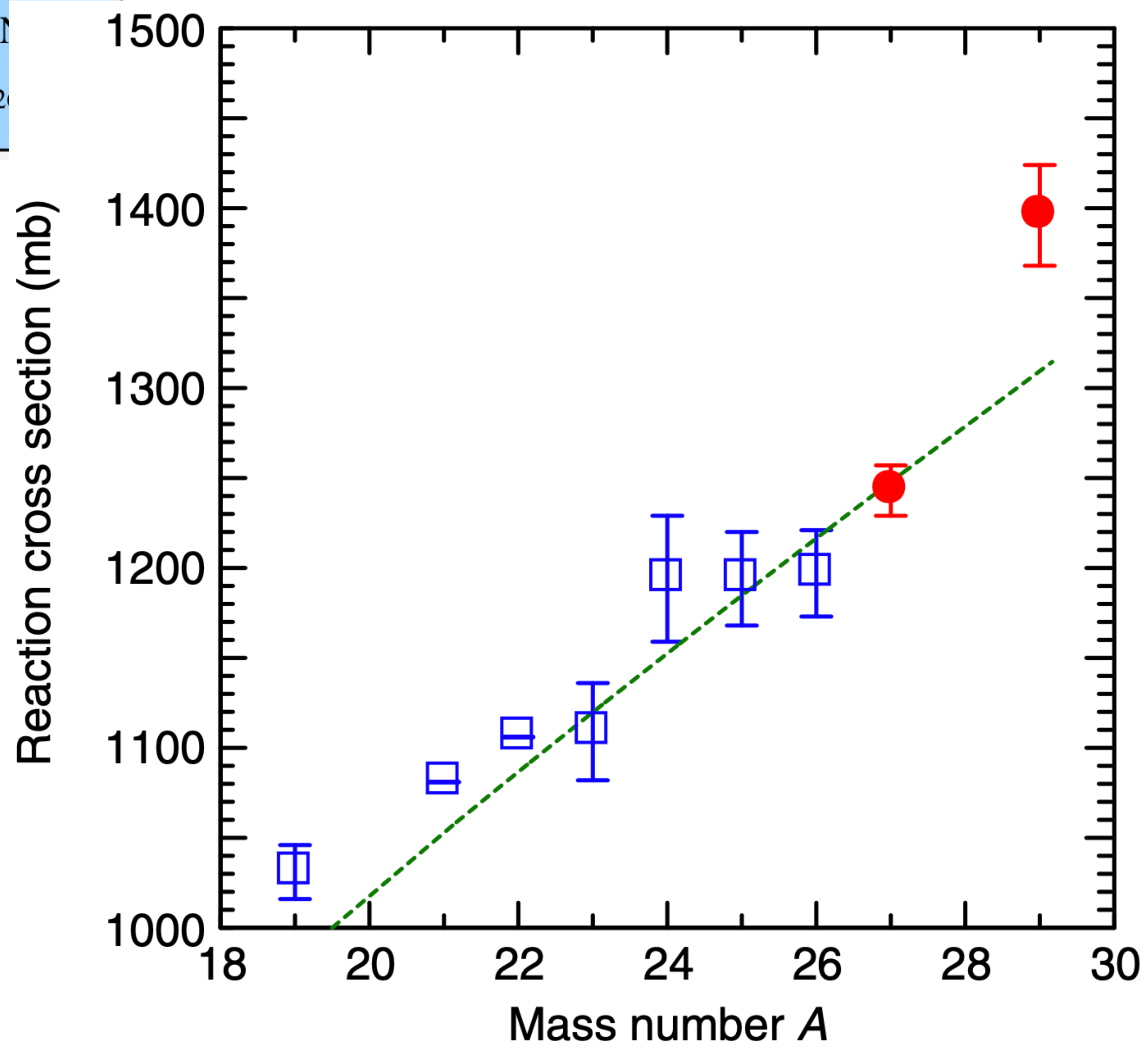
Continuum couplings decrease the $\nu 1p_{3/2}$-$\nu 0f_{7/2}$ gap.



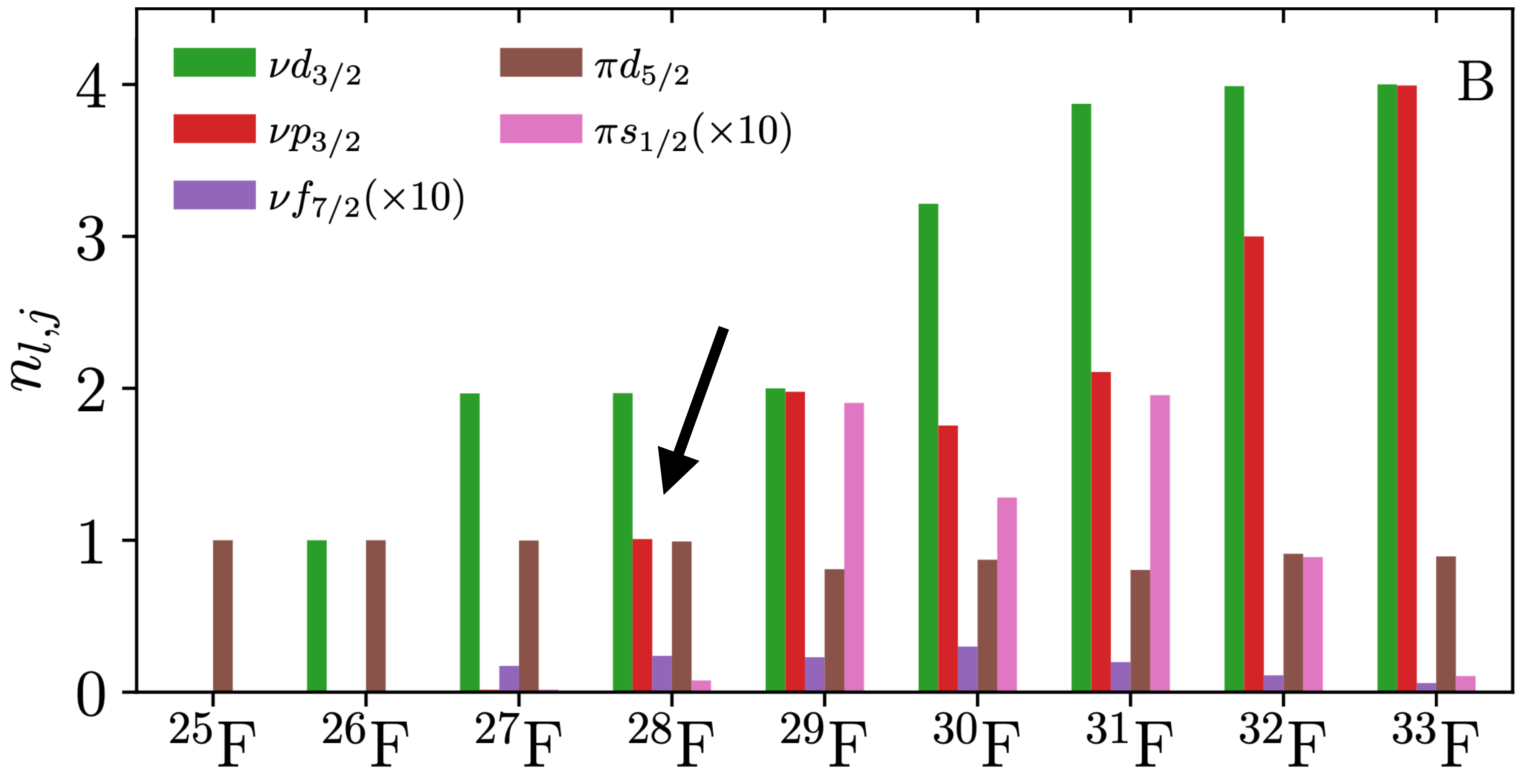


A. Revel et al., Phys. Rev. Lett. **124**, 152502 (2020)

S. Bagchi et al., Phys. Rev. Lett. **124**, 222504 (2020)



K. Fossez *et al.*, PRC **106**, 034312 (2022)



Suggestion for finding interesting mechanisms

Continuum-induced deformation: Look for areas where s/p-waves come down (neutron).

See H. Iwasaki's talk

→ 38Ne, 39Na (N=20) fill the 0f7/2, the 1p3/2 might go down as in 28-31F.

D. S. Ahn *et al.*, Phys. Rev. Lett.**123**, 212501 (2019)

→ 22Si (Z=14, N=8), should fill the 0d5/2 but the 1s1/2 might go down. Similar in neutron-rich N isotopes.

Universality: Look for situations with a well-bound spherical core + many neutrons like in neutron-rich He and O, and compare with their mirrors.

→ systematic of masses in neutron-rich C (Z=6), Ca (Z=20), and proton-rich N=6, 8, 20 chains.

→ correlations between the valence nucleons.

→ multi-neutron/proton decay (neutron-rich Be, O).

See D. Lee's talk

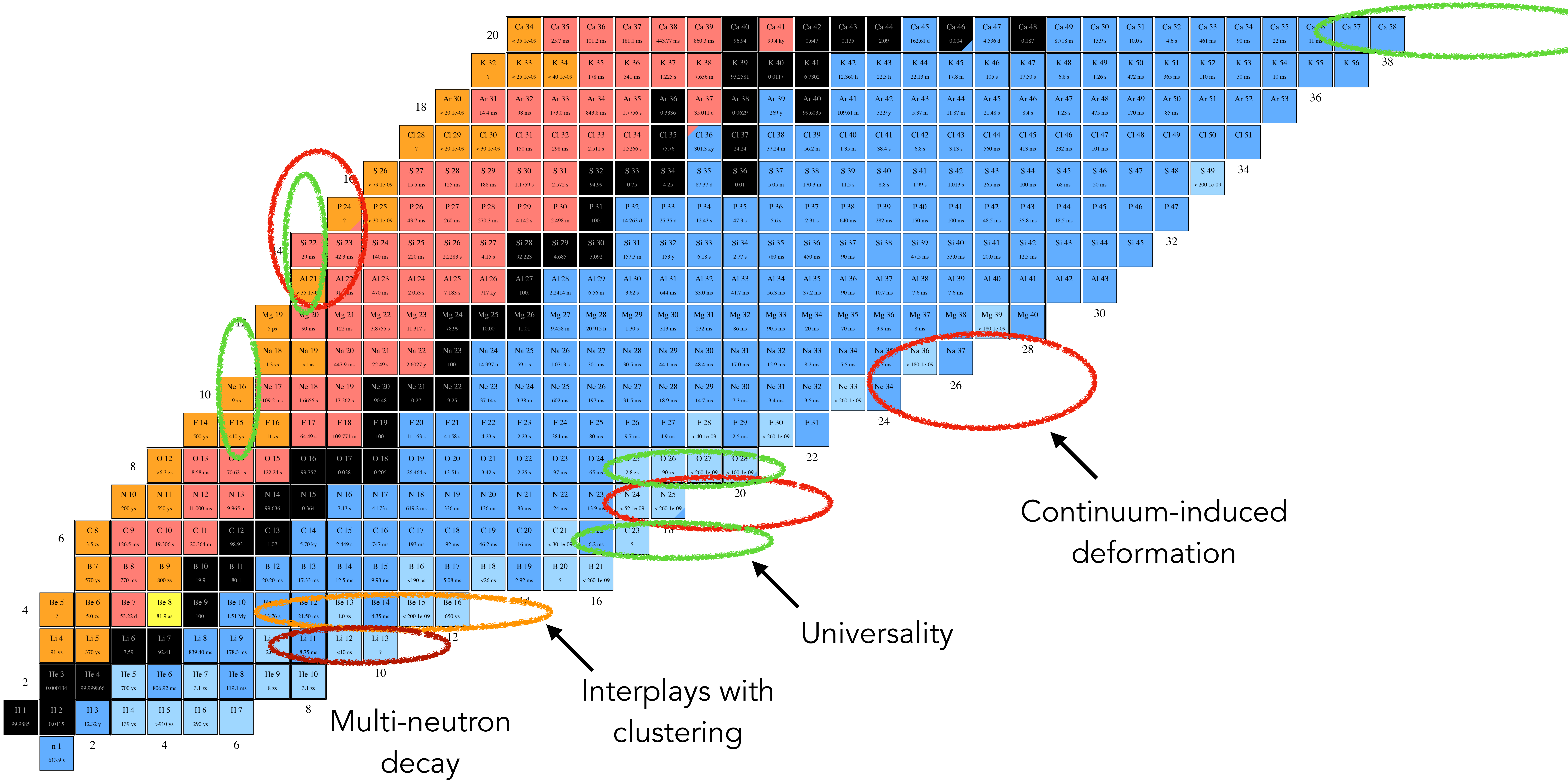
Interplays between week binding/decay and clustering:

→ radii/moments = f(N/Z) in deformed/clustered + weakly bound/unbound n/p (neutron-rich Li, Be).

→ look for systems with nearby proton, neutron, and cluster decay channels and search for new states.

See A. Volya's talk

Suggestion for finding similar mechanisms



K. Fossez, FSU - FRIB Bridge

Thank you for your attention!

DOE: DE-SC0013617 (Office of Nuclear Physics, FRIB Theory Alliance)